Unclassified

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1 SC

AD A091325

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. ~~REPORT NUMBER~~ AFGL-TR-80-0300	2. GOVT ACCESSION NO. AD-A092	3. RECIPIENT'S CATALOG NUMBER 325
4. TITLE (and Subtitle) ANGULAR DIAMETER OF THE ASTEROIDS VESTA AND PALLAS DETERMINED FROM SPECKLE OBSERVATIONS.		5. TYPE OF REPORT & PERIOD COVERED Scientific. Interim.
		6. ~~PERFORMING~~ ORG. REPORT NUMBER
7. AUTHOR(s) Simon P./Worden, Murray K./Stein * (10) (11) 24 May 78		8. CONTRACT OR GRANT NUMBER(s) (12) 5
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Geophysics Laboratory (PHS) Hanscom AFB Massachusetts 01731	(16)	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2311G311 (17) 63
11. CONTROLLING OFFICE NAME AND ADDRESS Air Force Geophysics Laboratory (PHS) Hanscom AFB Massachusetts 01731		12. REPORT DATE 2 October 1980
		13. NUMBER OF PAGES 3
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

~~Approved for public release; distribution unlimited.~~

DTIC ELECTE NOV 7 1980 S D B

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Reprinted from The Astronomical Journal, Volume 84, Number 1, January 1979

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Speckle interferometry
Asteroids
Vesta
Pallas

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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NTIS GRA&I	☑
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A	20/21

AFGL-TR-80-0300

THE ASTRONOMICAL JOURNAL VOLUME 84, NUMBER 1 JANUARY 1979

ANGULAR DIAMETER OF THE ASTEROIDS VESTA AND PALLAS DETERMINED FROM SPECKLE OBSERVATIONS

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Received 24 May 1978; revised 8 August 1978

ABSTRACT

The technique of speckle interferometric measurement of asteroids is applied to Vesta and Pallas, yielding diameters of 550±23 and 673±55 km, respectively. The improved Vesta speckle diameter is in excellent agreement with other measurements for Vesta. However, the derived Pallas diameter is slightly larger than other measurements. This is perhaps attributable to systematic errors arising as an object's angular diameter nears the seeing disk size. It is also pointed out that it is necessary to carefully normalize and center speckle frames before applying the autocorrelation,cross-correlation subtraction method developed by Worden *et al*. [Icarus 32, 450 (1977)].

I. INTRODUCTION

The use of speckle interferometry to obtain high-angular-resolution information has proven valuable since first proposed by Labeyrie (1970). A summary of the uses and limitations of speckle technique has been given by Worden (1977). The application of speckle techniques to the study of asteroids is appealing since it provides an alternate means of measuring their diameter to means such as radiometric flux measurements and polarization observations. (See Morrison 1977 for a review.) In previous work (Worden *et al.* 1977, Welter and Worden 1978) a method utilizing speckle interferometry to derive diameters for low-surface-brightness objects such as asteroids was developed and used to derive an angular diameter for Vesta. It is the purpose of this report to extend this method towards deriving a more accurate diameter for Vesta as well as obtaining a diameter for Pallas.

II. DATA AND METHOD

Speckle data consist of a series of short-exposure ($t \lesssim 0.05$ s) photographs at large image scales. On time scales short enough to freeze turbulent motions in the earth's atmosphere, a large telescope behaves as a multiple-aperture interferometer with a measurable modulation transfer function down to the telescope diffraction limit. This means that angular details on scales similar to the finest theoretical scale may be observed. The instrument used for these observations was the Kitt Peak National Observatory 4-m telescope and speckle camera described by Lynds, Worden, and Harvey (1976). The data consisted of a set of 180 35-mm Tri-X exposures for Pallas and 360 exposures for Vesta obtained on 3 February 1977 UT, with exposure times of 0.03 s. To preserve the interferometric character of such photos it is necessary to limit the bandpass of observations, in this case to $\Delta\lambda = 300$ Å at 5500 Å. Although not specifically required, point source stars were also observed. A summary of these observations is given in Table I.

The method used to reduce these observations follows that presented in Worden *et al.* (1977). The end product of this method is the autocorrelation of the diffraction limited image $O(x,y)$ given mathematically by

$$O(\Delta x,\Delta y)*O(\Delta x,\Delta y) = \int\int O(x,y)O(x+\Delta x, y+\Delta y)dxdy. \quad (1)$$

From this function angular diameters may be obtained (but not images, since the autocorrelation loses phase information). As shown by Worden *et al.* (1977) the desired autocorrelation is derived by computing the mean autocorrelation of a set of speckle images $f_i (i = 1,\ldots, N$ for N speckle frames),

$$\langle f_i(\Delta x,\Delta y)*f_i(\Delta x,\Delta y)\rangle = \int\int f(x,y)f(x+\Delta x, y+\Delta y)dxdy. \quad (2)$$

TABLE I. Observations and results.

Object	Date (UT)	Angular diameter (arcsec)	Diameter (km)	Previous determination (Morrison 1977) (km)
Vesta	3 Feb 0500	0.470 ± 0.02	550 ± 23	538
Pallas	3 Feb 0655	0.73 ± 0.06	673 ± 55	608
48 Gem	3 Feb 0515	Point source	...	...
HR 3653	3 Feb 0705	Point source	...	...

[a] Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

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The mean cross correlation between this same set of speckle images is then computed, and then subtracted from (2). As shown in that paper, the result is the desired object autocorrelation in (1),

$$O(x,y)^*O(x,y) = \langle f_i(x,y)^*f_i(x,y)\rangle - \langle f_i(x,y)^*f_{i+1}(x,y)\rangle. \quad (3)$$

Several aspects of the reduction method have been learned which were not apparent in the original Worden *et al.* (1977) paper. We note here that it is necessary to normalize each frame so that the sum of intensities is the same from frame to frame. The reason for this procedure can be seen by considering two speckle frames modeled by identical Gaussians, one with a total area equal to 1, the second reduced by a multiplicative factor $1/2$. Following Bracewell (1965), we observe that the summed area of the autocorrelation is equal to $1^2 + 1/2^2 = 1.25$. Similarly, the summed area of the cross correlations between the two frames would be $2(1 \times 1/2) = 1$. The cross correlation should be identical to the autocorrelation in this case for our method to work. Consequently, it is necessary to normalize each speckle frame to the same value for integral area; otherwise the summed autocorrelation will always be larger than the cross correlations, even in the absence of a real speckle signal. A second problem arises from the fact that each frame is not digitized in a perfectly centered manner relative to the others. The autocorrelations will always be centered. However, if the two frames comprising the cross correlation are not centered relative to each other the cross correlation will be offset. If each frame in a given set is offset in a random manner this will mean that the summed cross correlation from this set will be spread out relative to the autocorrelation, giving rise to a spurious signal in the autocorrelation, cross-correlation subtraction. It is thus necessary to center each speckle frame before computing the correlation functions. This centering was necessary to remove the negative signal at large autocorrelation distances, comparable to the size of the seeing image (~0.5"). We found that centering to about 0.1" was adequate to eliminate this problem.

In practice the speckle frames for the asteroids and stars are scanned using the Kitt Peak PDS microdensitometer onto a 128 × 128-element array. The scanning aperture was 100 × 100 μ with a step size of 100 μ. This procedure results in a pixel resolution of 0.02" assuming a plate scale of (0.198 + 0.008)"/mm as measured by H. McAlister at the Kitt Peak National Observatory. This resolution undersamples the diffraction limit frequencies by almost a factor of 2. This was necessary to minimize the size of the arrays to be processed. For frequencies near the diffraction limit, this would cause aliased spectra for objects near the diffraction limit in size, such as point source objects. However, for large objects like Vesta and Pallas, there are no frequencies near the diffraction limit, so aliasing is not a problem. These data are then converted from measured plate density to relative intensities utilizing a standard curve measured for Kodak Tri-X film. Each frame is then digitally Fourier transformed using the Sacramento Peak Xerox Sigma 5 computer. As discussed by Bracewell (1965), the auto and cross correlations can be computed from the transforms $F_i(u,v)$ of the frames $f_i(x,y)$ as follows for the autocorrelation:

$$f_i^*f_i = \int\int F_i(u,v) \times F_i(u,v)\, exp[-i\alpha\pi(xu + yv)]\,du dv, \quad (4)$$

namely by inverse Fourier transforming the power spectrum. The cross correlation may be similarly obtained from the transforms of successive speckle frames. The correlations are then summed for 20-frame averages and subtracted as detailed in Eq. (3). This yields 8 estimates of the unperturbed autocorrelation for the 160 Pallas frames and 16 for the Vesta data. Similarly, 160 frames each for point source objects 48 Gem and HR 3653 were reduced.

To derive diameter estimates from these data, a best-fit estimate was computed for each 20-frame average between the derived result and theoretical autocorrelations computed for various diameter uniform disks. Due to the possible aliasing problem near the diffraction limit, we did not use the derived point source autocorrelation as a comparison autocorrelation. However, in other work we found that the point source autocorrelation did not differ significantly from the theoretical one. We also found that the diameters derived did not differ for the two methods provided we only used the higher-intensity portions of the program object autocorrelations (relative intensity ≥0.3) to derive diameter estimates. We have assumed no limb darkening for these objects, which is apparently a reasonable assumption (Zellner 1977). The estimates derived in this manner and the errors determined from internal consistency in the result are given in Table I along with other measurements of asteroid diameters.

The use of photographic data presents several possible difficulties. The most serious of these is the nonlinearity and nonuniform sensitivity of the film. These effects may result in improper normalization of frames, as discussed previously. The result of this error would be to reduce the cross correlations relative to the autocorrelation, thus increasing the measured diameter of the object. Another effect which may be present is scattered light in the system. This would also result in a possible increase in the diameter. A sample of the reduced data is shown in Fig. 1, a radial average of the correlation difference for Pallas, Vesta, and point source comparisons. Both of the point source reductions showed sizes close to the theoretical diffraction-limited autocorrelation. However, the low-intensity portion of the point source reduction does show some increase in size which may perhaps be attributable to the effects outlined above. This would be expected to affect the Pallas diameter more severely, since it has a size nearer to the seeing disk. Consequently, the speckle signal is lower and more affected by systematic errors. Since the measured diameter is slightly

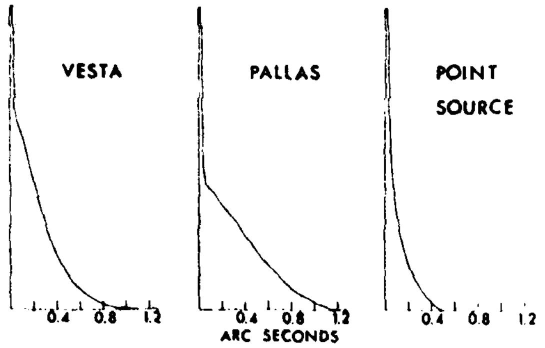

FIG. 1. One-dimensional radial average of autocorrelation minus cross correlation for one 20-frame set for Vesta, Pallas, and 48 Gem. Each autocorrelation has been normalized to unity.

larger than other measurements, this may in fact be the case. Another possible source of error is due to the fact that the asteroids have a very low surface brightness, and the photon noise would effect each telescope resolution element much more than the much brighter (point by point) star images. However, reduction of 10th-magnitude star images from a new digital camera we are testing indicates that this is not a serious problem even with as few as 80 frames.

III. CONCLUSIONS

We have applied a correlation method for the reduction of speckle interferometry data towards further analysis of asteroid speckle interferometry data. Further, we have derived an improved diameter for the asteroid Vesta of 550 ± 23 km, in excellent agreement with other measurements. We have also presented a measurement of Pallas of 673 ± 55 km, slightly larger than previous measurements. However, Pallas has an angular extent close to the telescope seeing limit, and the diameter may be affected by several systematic effects resulting from the use of a photographic recording system. New measurements are planned utilizing linear digital detector systems to reduce the effects of these errors.

We have also pointed out in this paper the necessity of normalizing and centering each speckle frame before reduction, for otherwise the diameter derived may be spuriously large.

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